Photons to search for new phenomena with the ATLAS detector

with an emphasis on the
ATLAS-CONF-2022-018
preliminary results, first presented at Moriond QCD 2022

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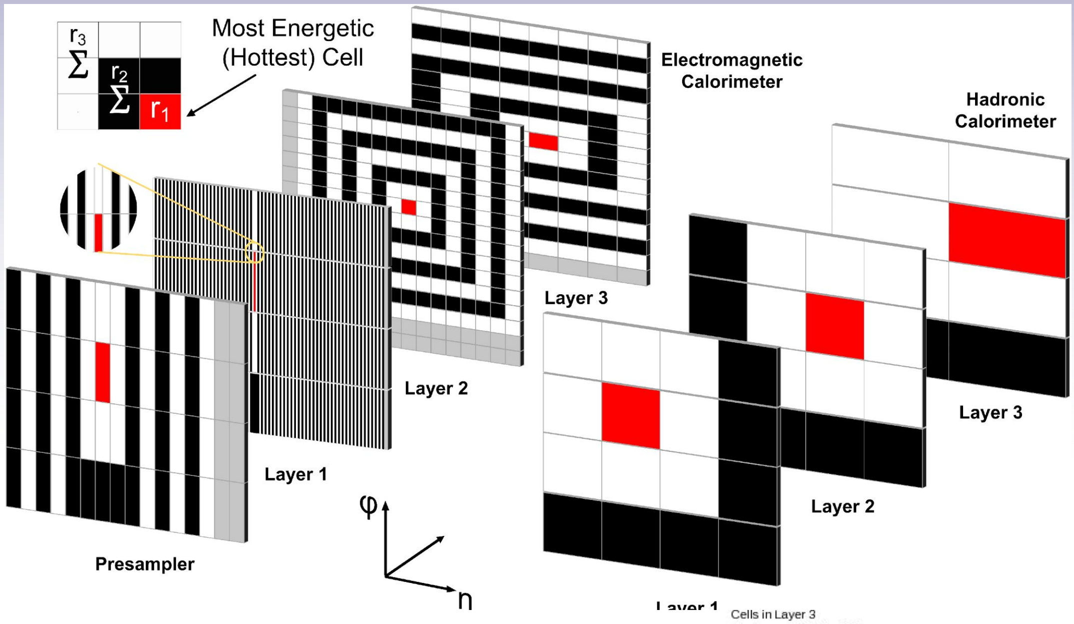
The ATLAS liquid Argon calorimeter (LAr)

Sampling electromagnetic calorimeter

- measures energy of photons (and e)
- interleaves layers of lead (absorber) and liquid Argon
- longitudinally segmented into three layers
- provides an excellent photon energy resolution :

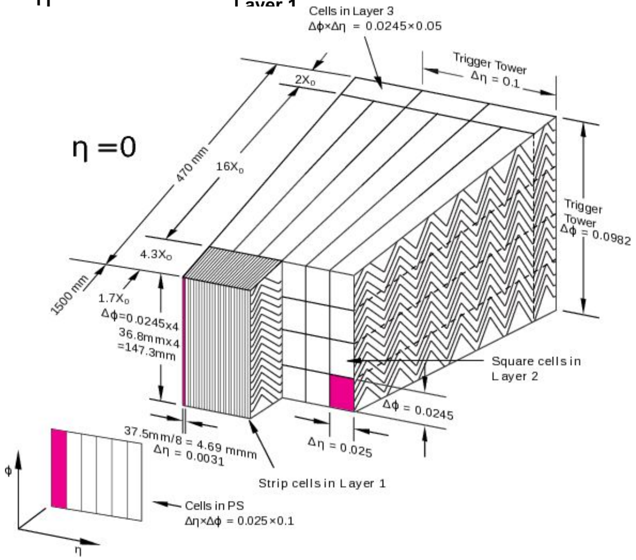
$$\frac{\sigma(E)}{E} = \frac{10\,\%\sqrt{GeV}}{\sqrt{E}} \oplus 0.7\,\%$$

crucial for the Higgs boson discovery in 2012 !



Hadronic calorimeters

- complement energy measurements (jets and taus)

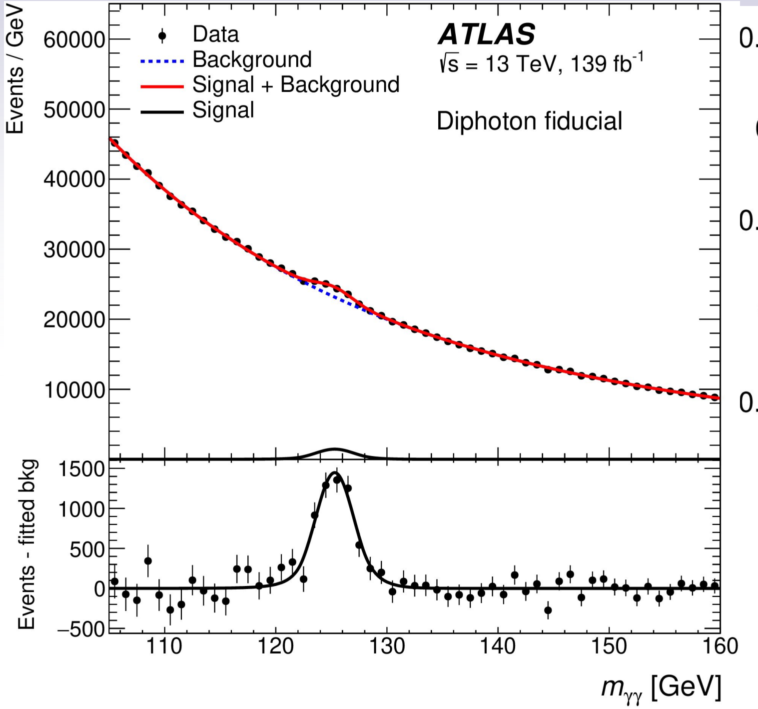


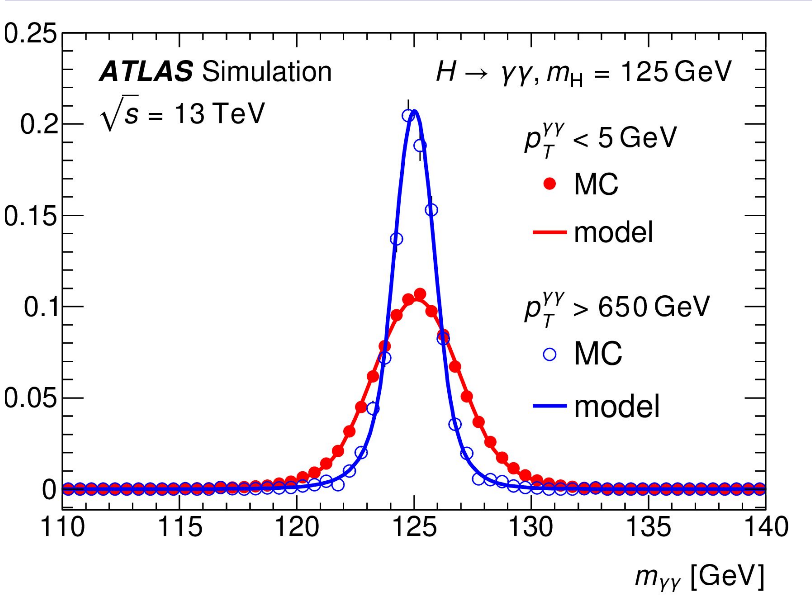
Energy deposits in calorimeter cells clustered together into “topoclusters”

- dynamical objects that span over all layers
- matching of tracks and clusters to
    - identify photons
    - discriminate from other objects in the calorimeters

Photons and the Higgs boson

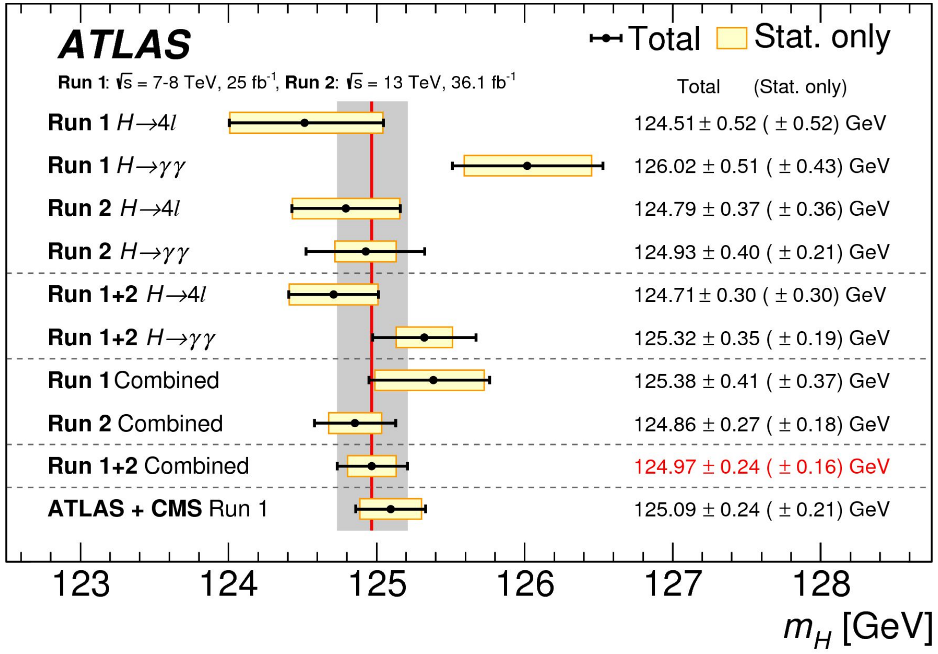
The $H\rightarrow\gamma\gamma$ channel provides several of the cleanest signatures for the study of Higgs boson properties





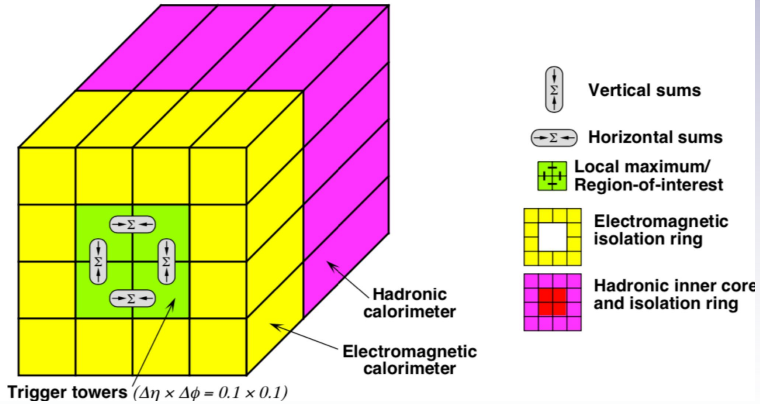
Higgs boson mass :

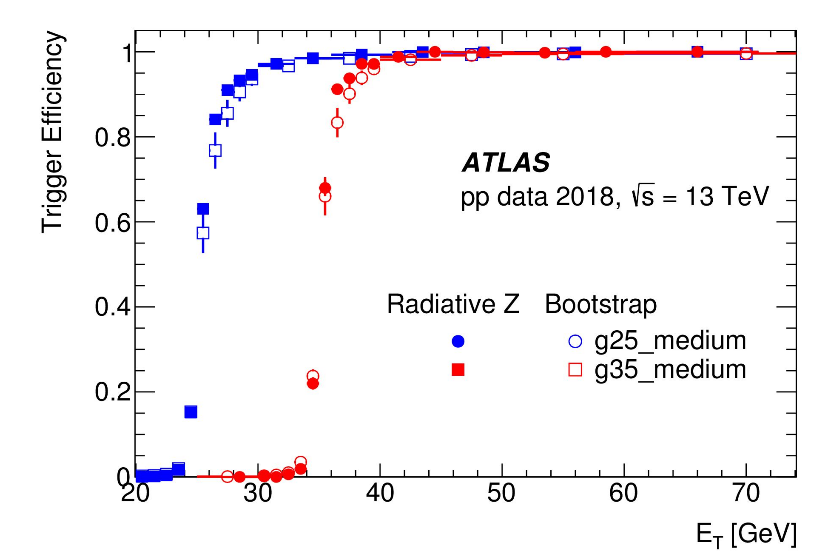
- precision measurement, at ±0.17% level
- $H\rightarrow\gamma\gamma$ precision comparable to $H\rightarrow 4l$ that benefits from a very clean S/B but suffers from a low signal rate



- despite large backgrounds from QCD (di)photons
- clear, narrow $m_{\gamma\gamma}$ signal
- excellent invariant mass resolution
  - typically in the order of ±1.5 GeV to ±2 GeV
  - can be as low as ±1 GeV for the hardest photon pairs

Photon performances: trigger





- Two-level photon triggers based on
  - readout of towered energy sums around ROIs at L1
  - close-to-complete reconstruction at HLT
- Thresholds on transverse energy are needed to cope with overwhelming rates
  - excellent efficiency plateaus above the thresholds
- Thresholds and criteria vary with luminosity and data-taking periods
- A diphoton trigger combines two separate single-photon triggers

Year	2015	2016 up to D3	2016 from D3	2017	2018
L1 item	L1_2EM10VH	L1_2EM15VH	L1_2EM15VH	L1_2EM15VHI	L1_2EM15VHI
HLT item	2g20_tight	2g20_tight	2g22_tight	2g20_tight_icalovloose	2g20_tight_icalovloose
luminosity $[fb^{-1}]$	3.2	11.5	21.5	43.6	58.5

Photons (and electrons) : very similar development of electromagnetic showers in a uniform calorimeter

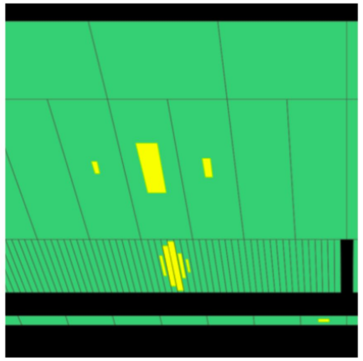
- (almost) invariant lateral and longitudinal developments

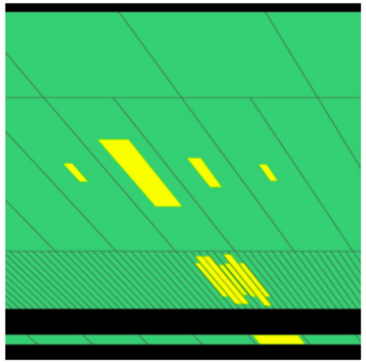
An e/gamma candidate is a “super-cluster” arrangement of topoclusters, compatible with an EM shape

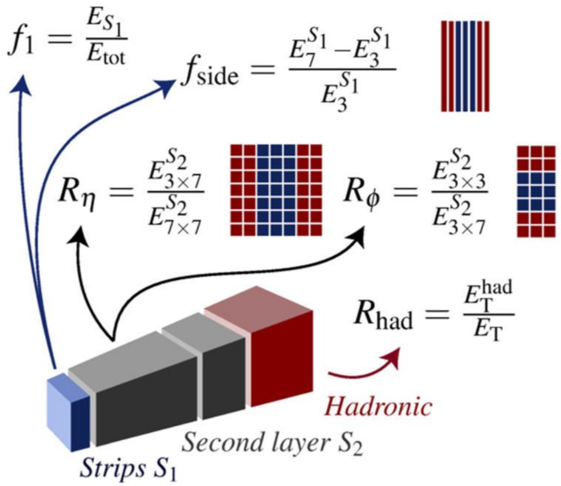
- multivariate selection on a collection of correlated “shower-shape” variables
- for photons, selection is optimized to reject “fake” candidates (mostly neutral hadrons in jets)

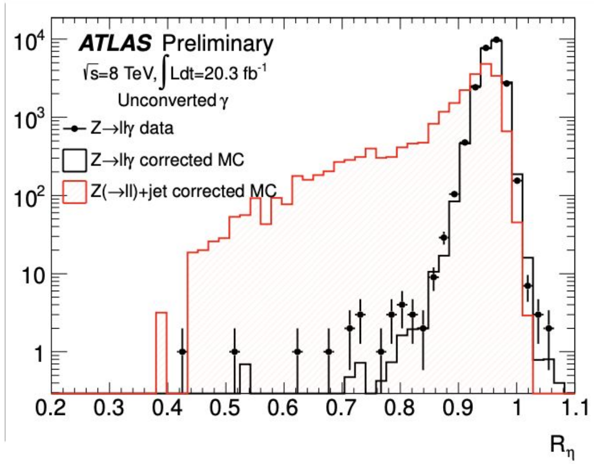
Photon-ID:

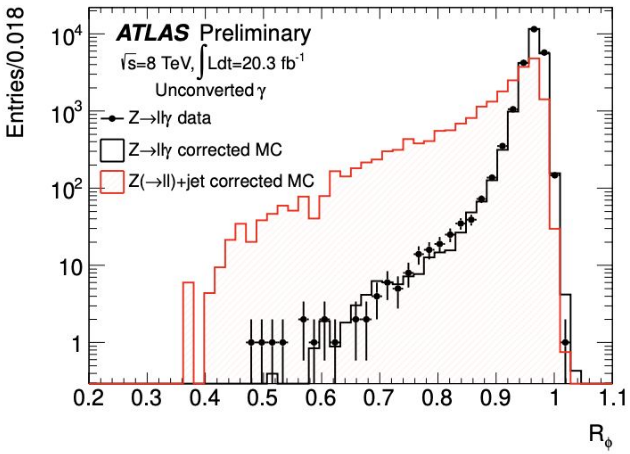
- high-granularity of the EM calorimeter plays a crucial role

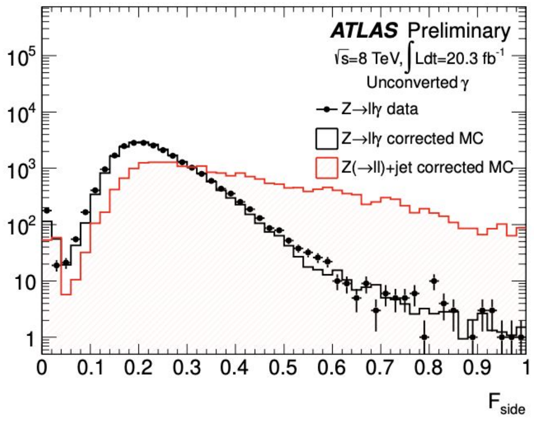












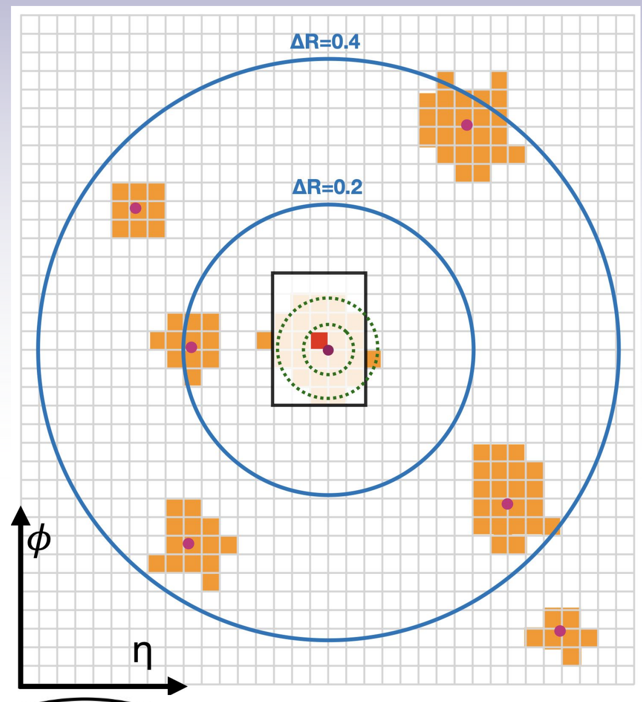
Photon performances: isolation

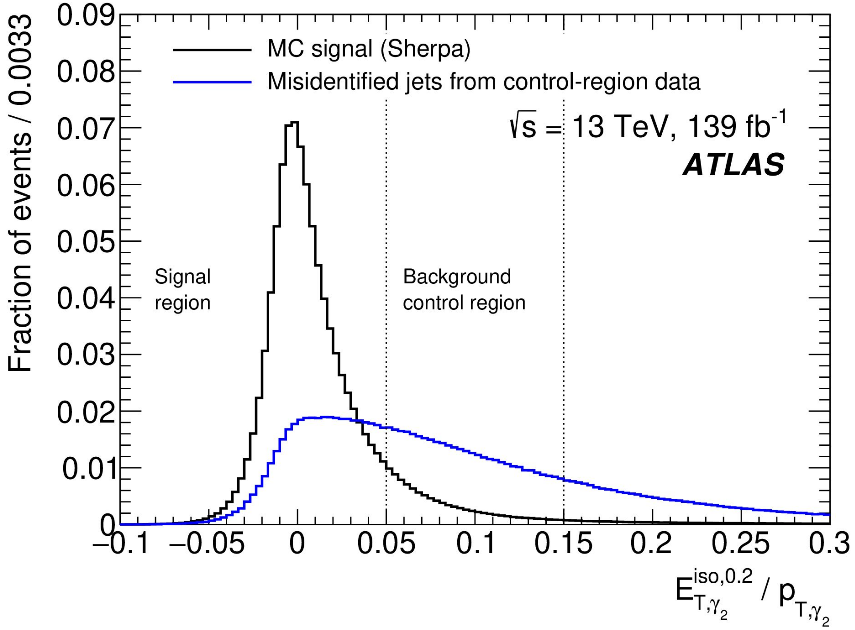
Photon isolation rejects further backgrounds on top of photon ID

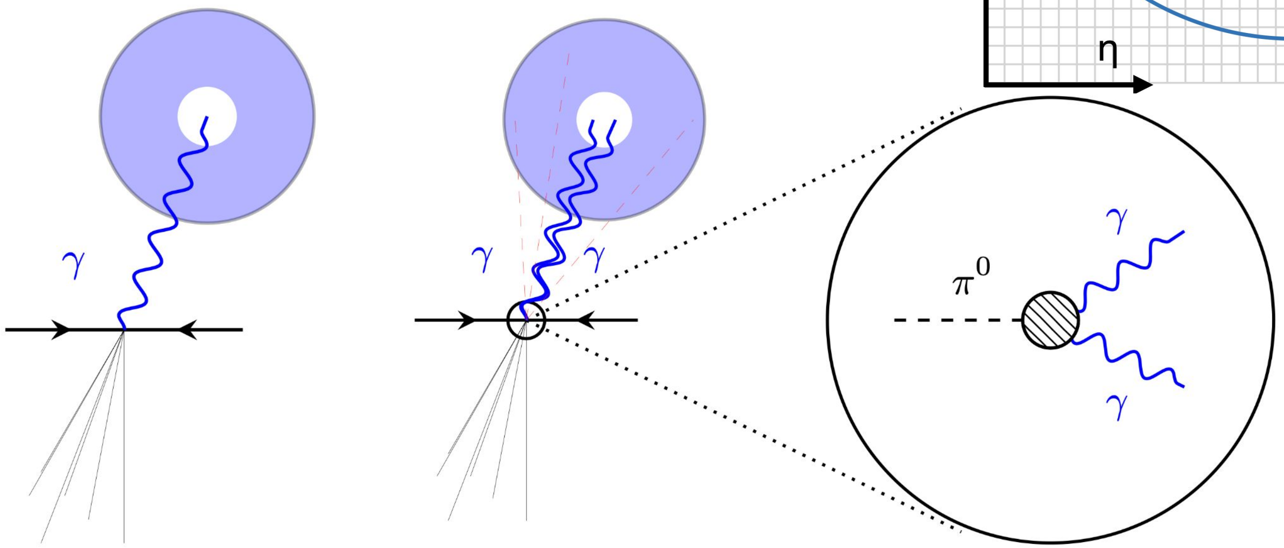
- fakes are usually surrounded by additional particles
- calorimetric isolation energy :

$$E_T^{\text{iso}}(R) = \left(\sum_{r_i<R}^{\text{clusters}} E_T^i\right) - E_T^{\text{corr}}(E_T^{\gamma}, \eta^{\gamma}, \langle\mu\rangle)$$

- sum of topocluster transverse energies within a ΔR cone around the candidate
  - corrections to account for various effects (pileup…)
  - the ΔR size impacts diphoton selections
- complemented with a track-based definition for charged particles around candidates



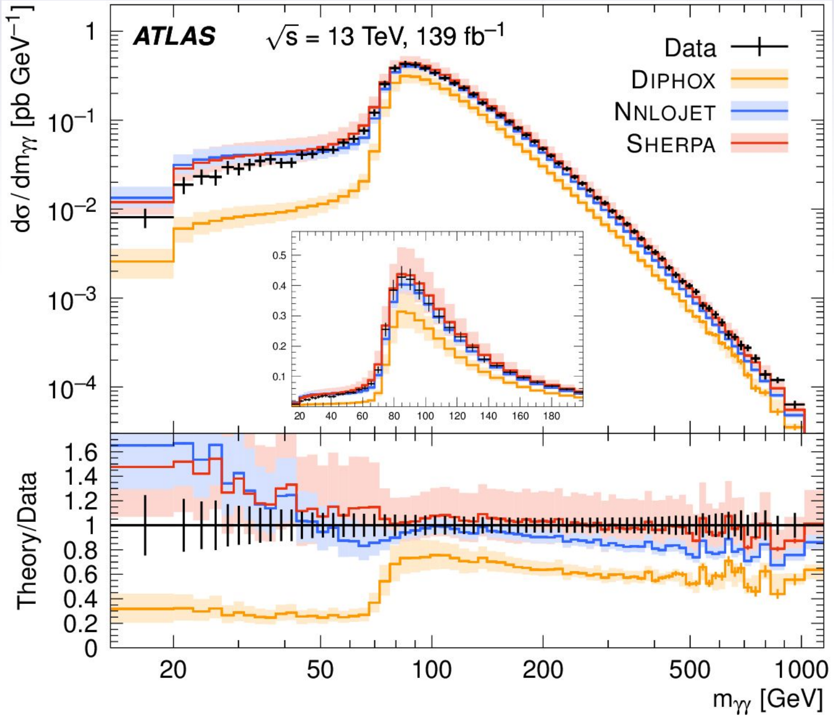


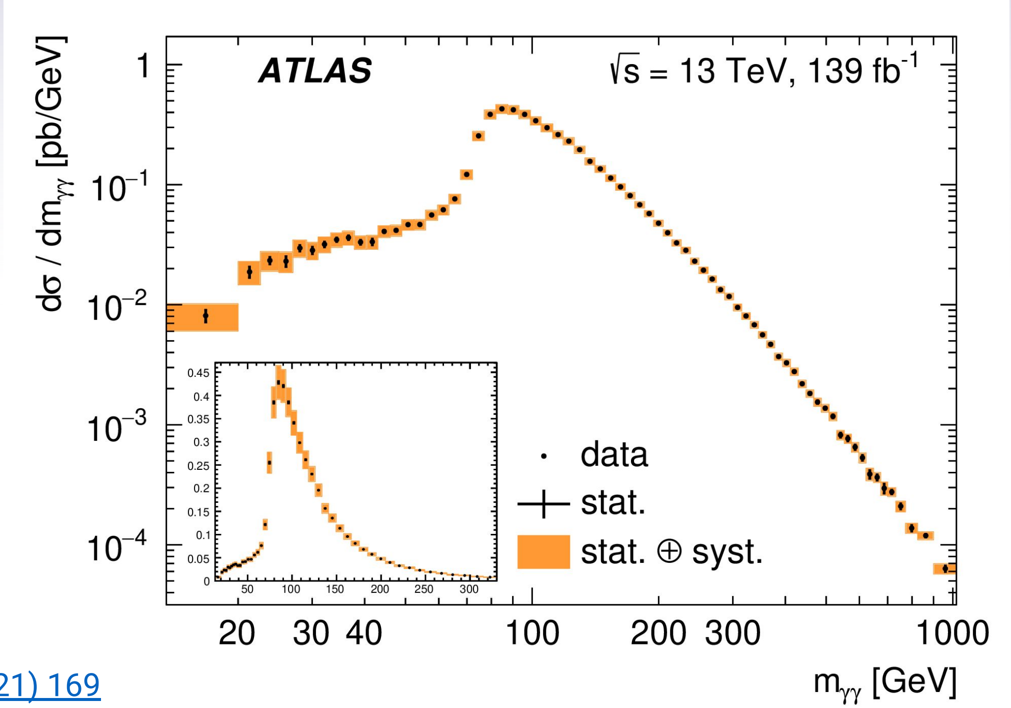


Measurements of the SM QCD diphoton production

(made@ITKP) study of diphoton production in pp collisions

- differential cross-sections, as function of $m_{\gamma\gamma}$, $p^T_{\gamma\gamma}$ and angular distributions of the photon pair
- precision tests of both the SM predictions and phenomenological models





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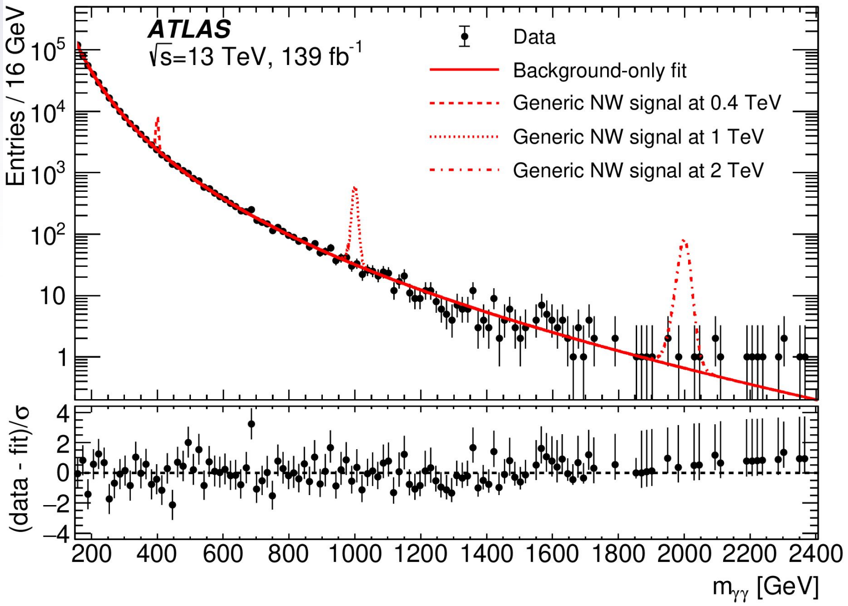
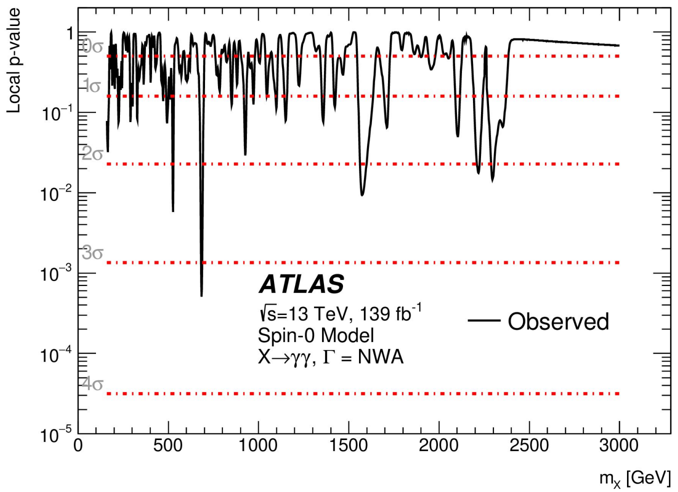
The SM predicts only one particle decaying into pair of photons in the ≳ 10 GeV mass range : the Higgs boson :-)

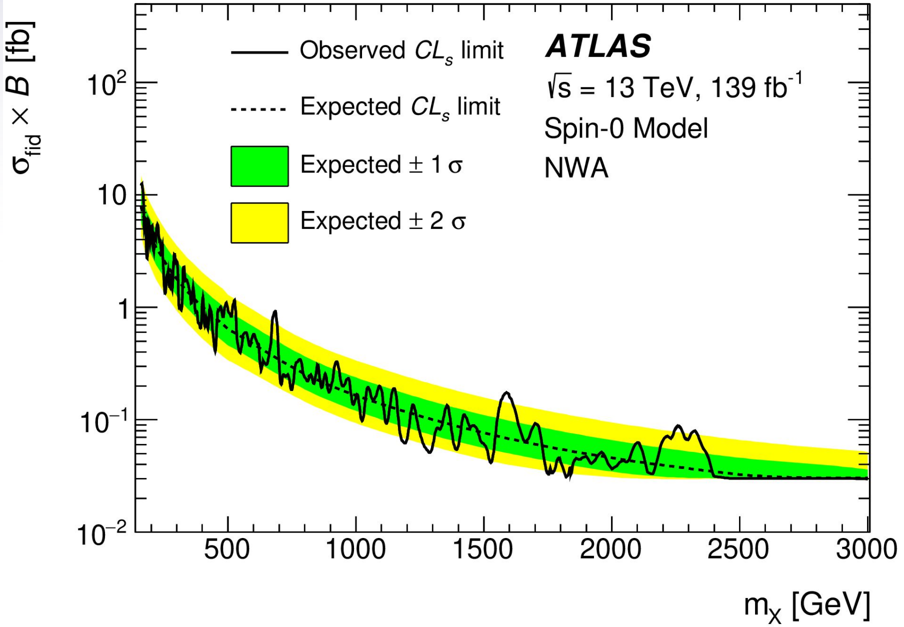
- many such new particles appear in a number of models beyond the Standard Model
  - among others, extended Higgs sectors lead to the prediction of additional neutral Higgses
- could there be other resonant peaks above the SM QCD diphoton spectrum ?

Searches for new particles with the diphoton channel (I)

- ATLAS and CMS have searched for diphoton resonances, in mass ranges above the Higgs mass
  - analysis strategies very similar to the ones optimised for the 125 GeV Higgs boson
  - a smooth, monotonically-decreasing background, dominated by QCD diphotons







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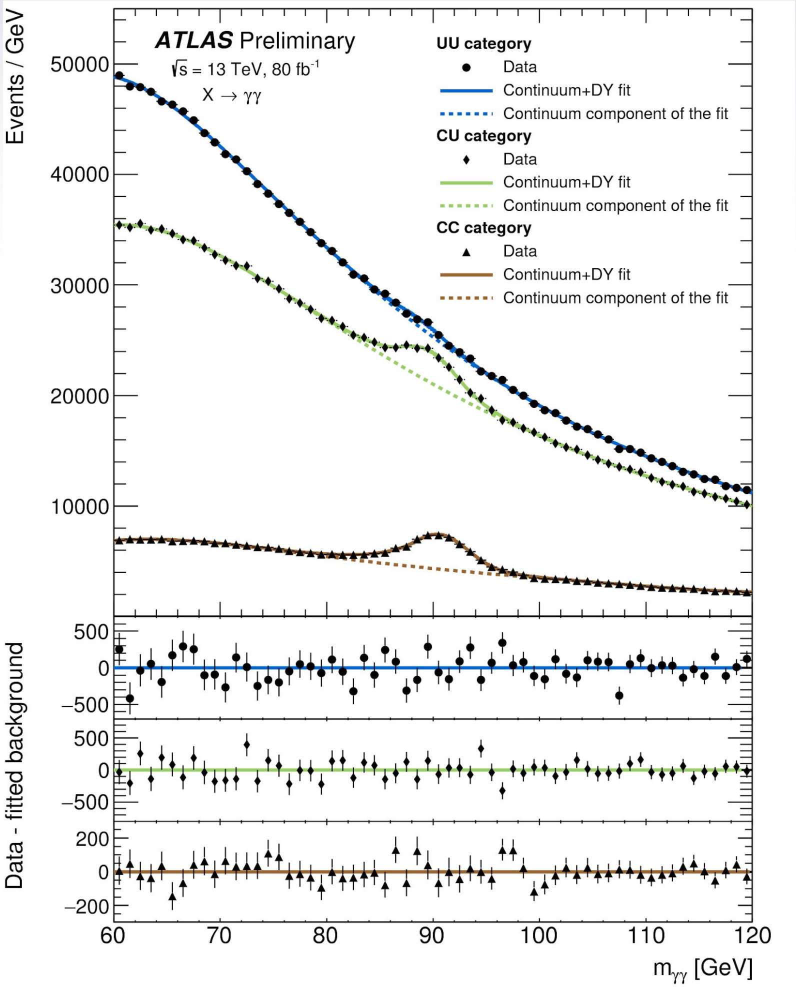
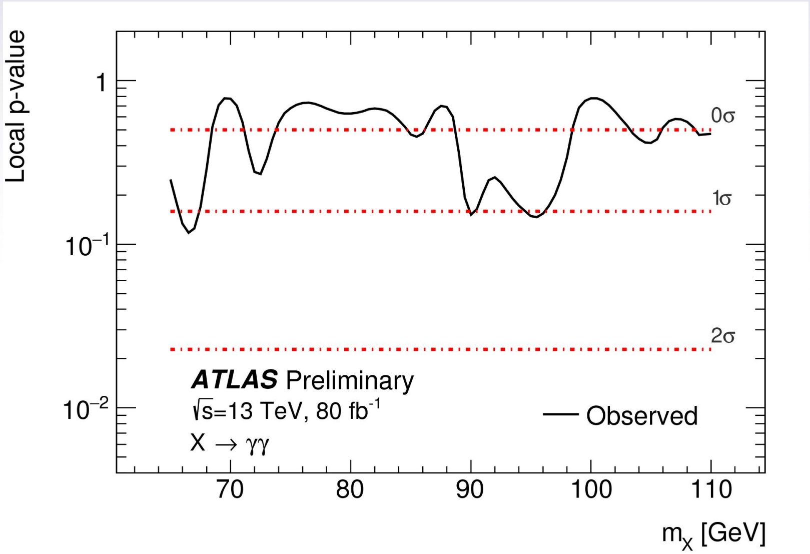
A large number of statistically independent mass subranges are explored

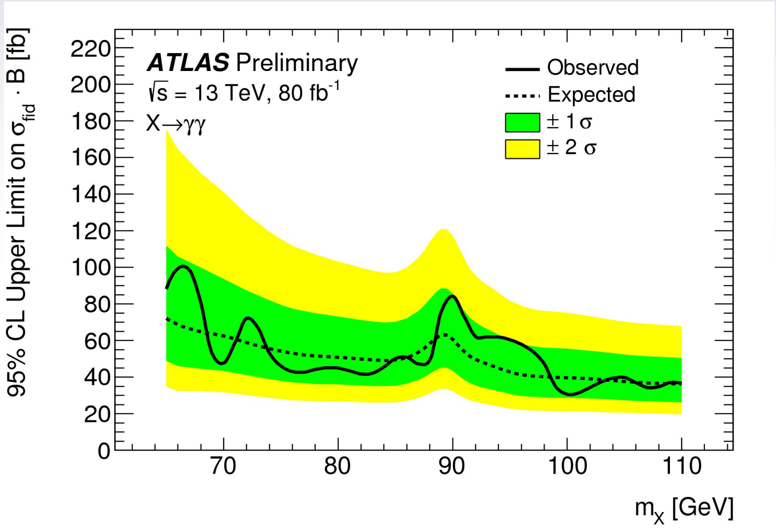
- owing to the excellent performances on photon performances, in particular energy calibration
- the rate of local fluctuations is compatible with the global expectations
  - beware of over-interpretations :-)
- results are interpreted as limits in the production and decay rate of a hypothetical, new, heavy, “X” particle
  - the exclusion limits span from 200 GeV to ~2.5 TeV

Searches for new particles with the diphoton channel (II)

- ATLAS and CMS have also searched for diphoton resonances, in mass ranges below the Higgs mass
  - analysis strategies again very similar to the ones optimised for the 125 GeV Higgs boson
  - splitting the sample into photon conversion categories important to account for the Z background







Sensitivity strongly impacted by the difficulty in controlling the background shape

- the infamous “spurious signal” issue…
- shape below 60 GeV dominated by the trigger “turn-on” effect

A different approach is needed to reach lower masses!

- Several proposals for resonant Axion-Like Particles within the LHC mass reach
    - pNGBs associated to a spontaneously broken approximate symmetry above the TeV scale
- main interest as a possible DM mediator due to its weakly interacting nature
- ALPs below the Higgs mass would couple predominantly to gluons and photons
    - LHC is the natural laboratory to search for them !

- existing search gap in $\gamma\gamma$ channel resonance searches
- goal: push the current *65 GeV* limit towards lower masses, close the gap as much as possible !

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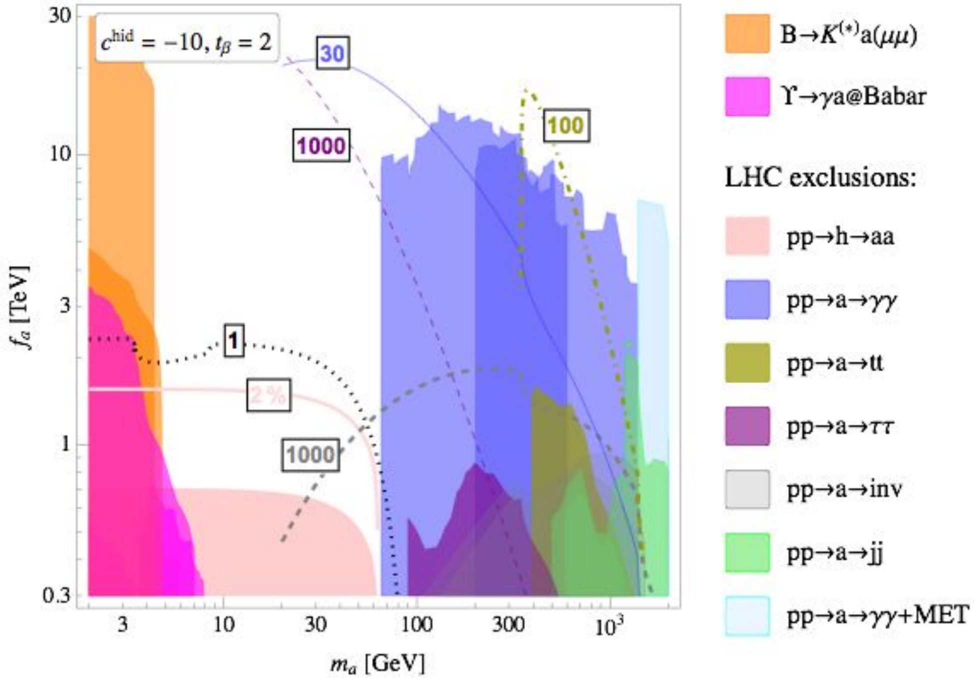

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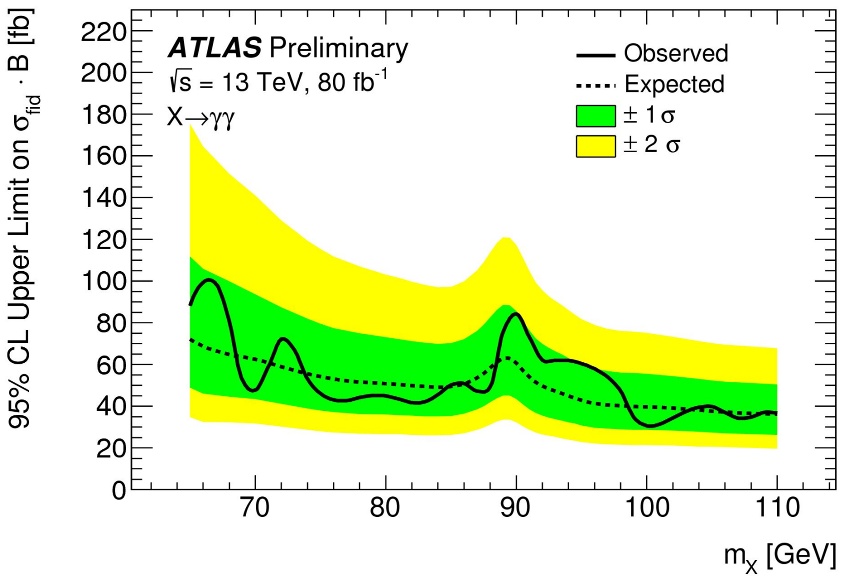

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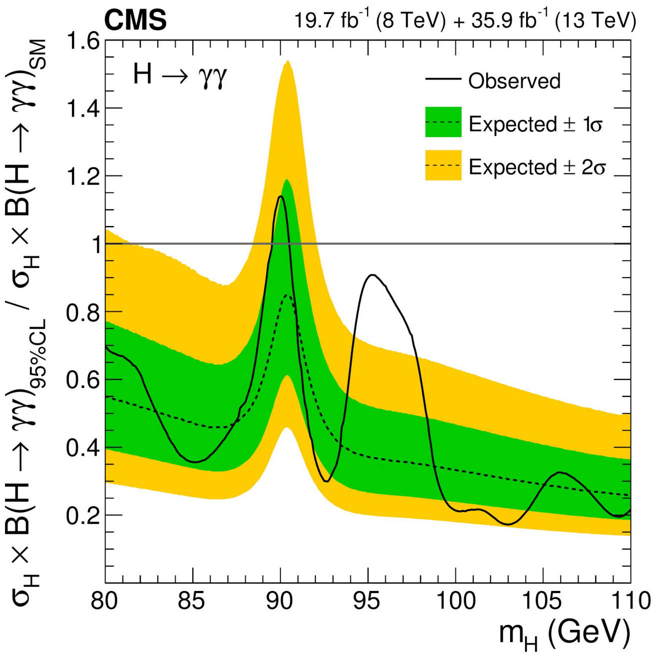
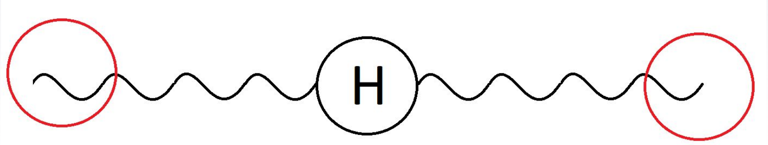
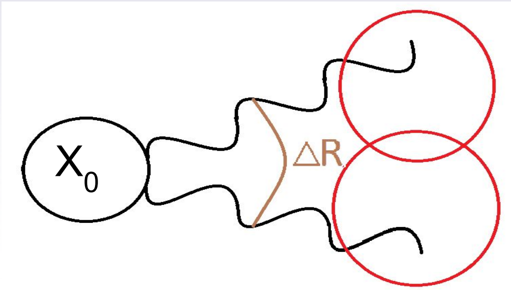


The “standard” ATLAS diphoton analysis has been mostly optimized for the study of the Higgs boson



$$m_{\gamma\gamma} = \sqrt{2E^{\gamma}_{T,1}E^{\gamma}_{T,2}[\cosh(\eta_2 - \eta_1) - \cos(\Phi_2 - \Phi_1)]}$$

- Most photons are emitted back-to-back
- Their E^T spectrum are largely within the trigger plateaus
- Standard photon isolation has very good performances
- A diphoton candidate is just the combination of two single-photon candidates



$$m_{\gamma\gamma} \approx \sqrt{p^{\gamma}_{T,1}p^{\gamma}_{T,2}}\Delta R$$

To attain small X0 masses, two conflicting possibilities :

- reach lower E^T values
  - (but the trigger...)
- reach smaller angular separations
  - (but the isolation...)

Analysis strategy

Main limiting factors to reach diphoton masses below *65 GeV* :

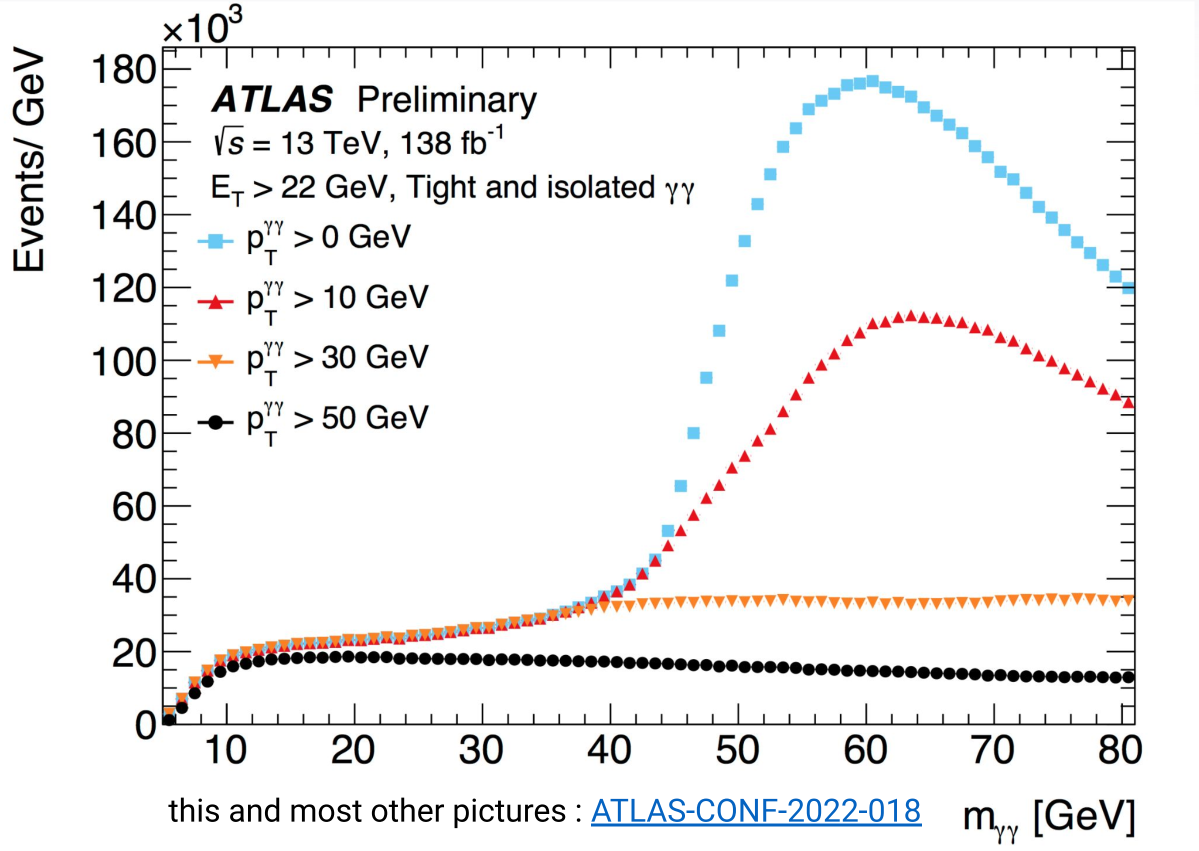
- diphoton trigger E_T thresholds at *20 GeV*
    - reduces signal acceptance
    - limits background modelling with analytical functions due to steep trigger turn-on
- decrease in photon identification and isolation efficiencies for low-ET photons

This analysis follows standard ATLAS diphoton selections

- data recorded with unprescaled diphoton triggers
- trigger thresholds and criteria evolved during Run-2
    - *20 GeV* E_T thresholds for most data (except for *21.6* fb^{-1} in 2016 with a *22 GeV* threshold)
    - additional trigger-level isolation criteria in 2017+2018
- two reconstructed photon candidates with E_T*>22 GeV*
    - within the $|\eta|$ acceptance
    - passing *tight identification* criteria
    - passing *tight isolation* criteria (calorimetric+track)
- isolation computed in a *ΔR<0.2* cone around the candidate

Events at low mass have large transverse momentum $p_T^{\gamma\gamma}$

- add a boosted diphoton selection : $p_T^{\gamma\gamma}$ *> 50 GeV*
- results in a smooth background spectrum down to *10 GeV*

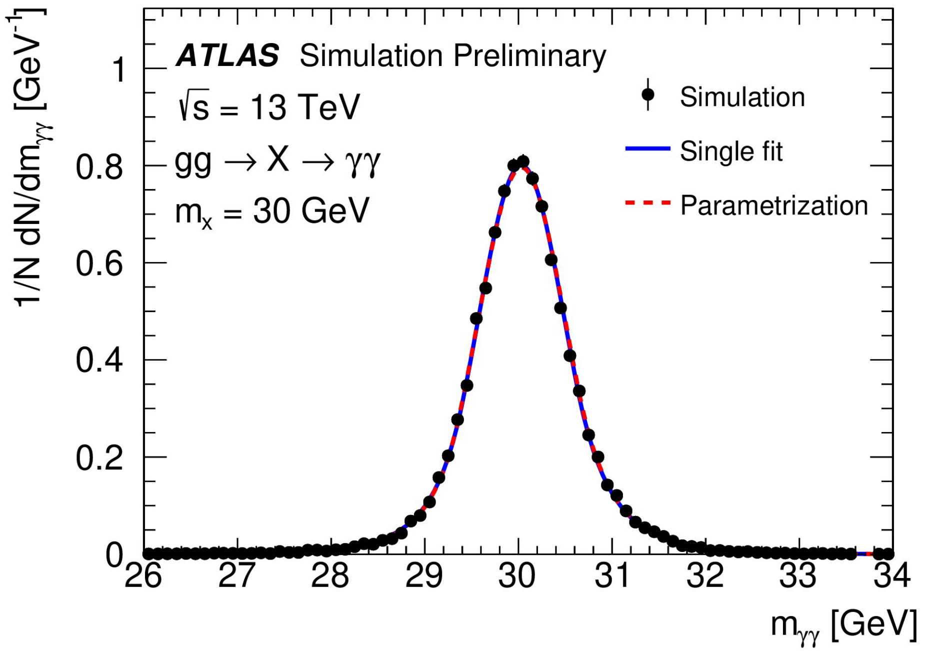


this and most other pictures : [ATLAS-CONF-2022-018]

Signal control samples and Signal modelling

- Signal MC control samples :
  - EFT framework: scalar “Higgs-like” resonance
  - gluon-fusion production only
  - generated with MadGraph at LO+0,1,2 jets

- Invariant diphoton mass resolution described with a Double Sided Crystal Ball (DSCB) function
  - narrow-width approximation (fixed *Γ = 4.07 MeV*)
  - DCSB parameters are linear functions of the mass point being tested
  - biases on fitted signal yields below the ±1% level on the full mass range



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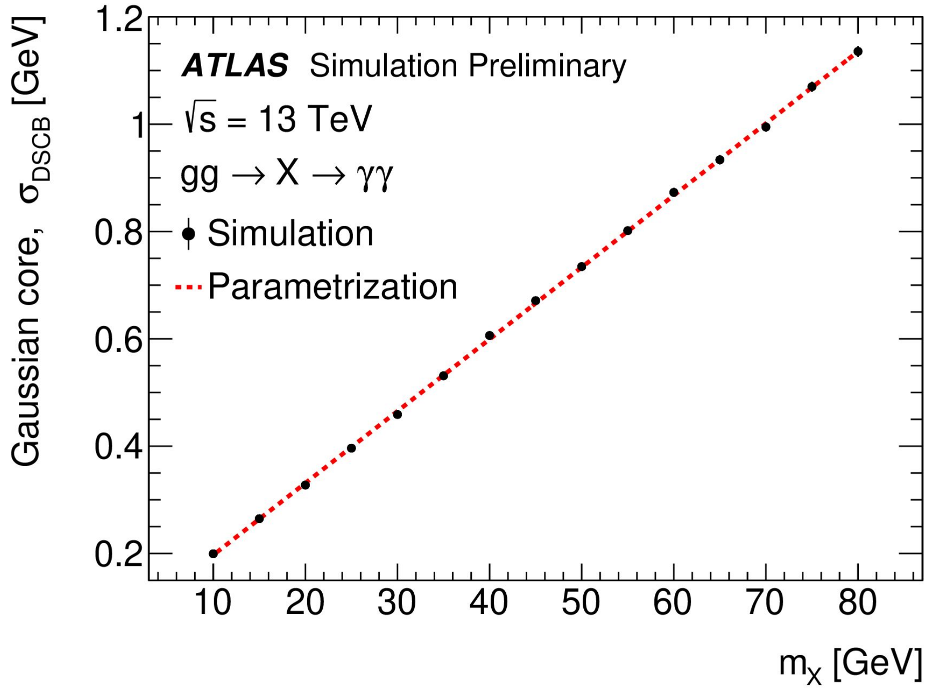
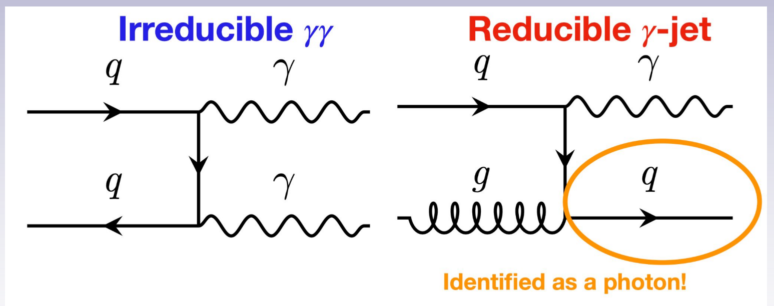


Background composition

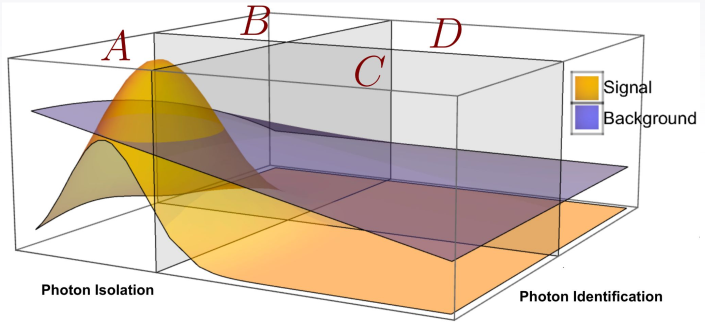
Non-resonant backgrounds:

- irreducible ($\gamma\gamma$) from QCD diphoton production
- reducible (γj+$j\gamma$+jj) from QCD with 1 or 2 jets misidentified as photon
- other backgrounds (i.e. from electrons) found to be negligible



Extract composition from double-ABCD method (aka 2x2D)

- using Isolation and Identification on each photon
- irreducible shapes extracted from Sherpa QCD diphoton
- reducible shapes extracted from control regions in data
  - photon candidates failing a subset of identification criteria



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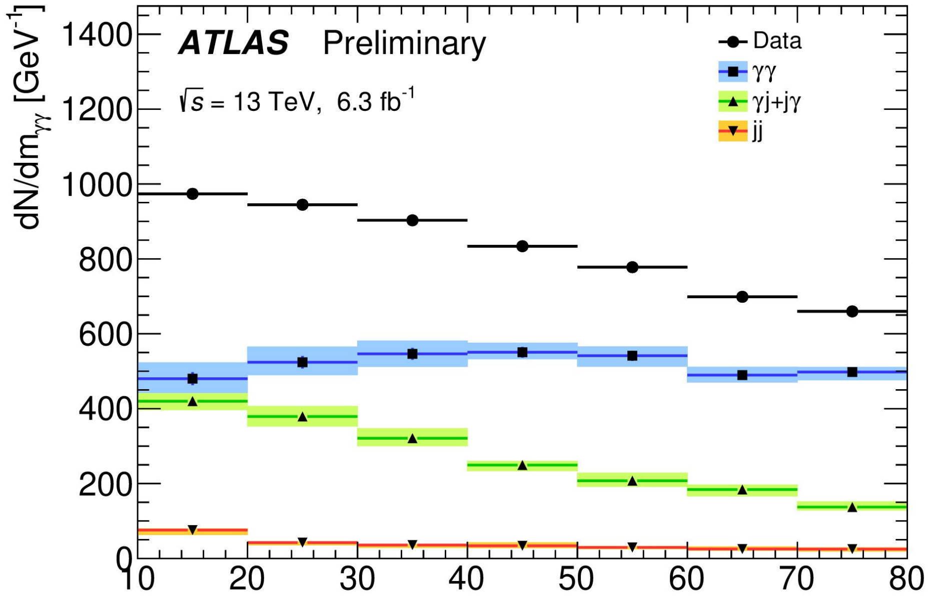

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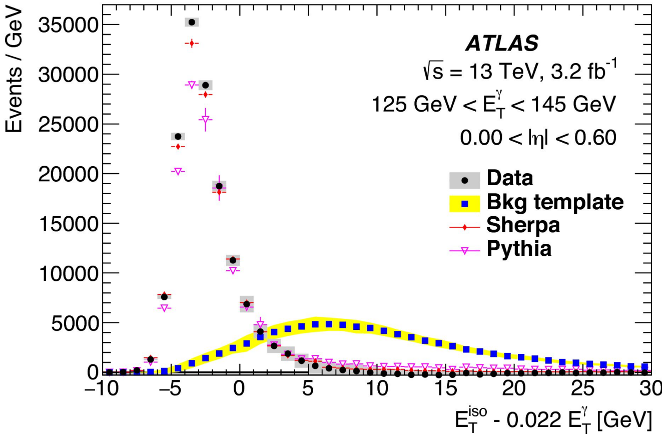
2x2D composition on a control sample passing a (prescaled) diphoton trigger with looser trigger-level ID requirements

large diphoton purity at higher masses

reducible background becomes dominant at very-low masses



JHEP 09 (2016) 001 (for illustration only)

Background modelling

Background shape qualitatively divided into two regions:

- fast turn-on region for masses below *~20 GeV*
  - described with an exponentially-saturating function (“Flat”)
- slowly decreasing region above, with a mild change in curvature between the mid- and higher- mass regions
  - described with the product of a power-law (“PowLaw”) times an “Activation” function

$$f\left(m_{\gamma\gamma}, \vec{\theta}\right) = Flat + \left[PowLaw \times Activation\right] =$$

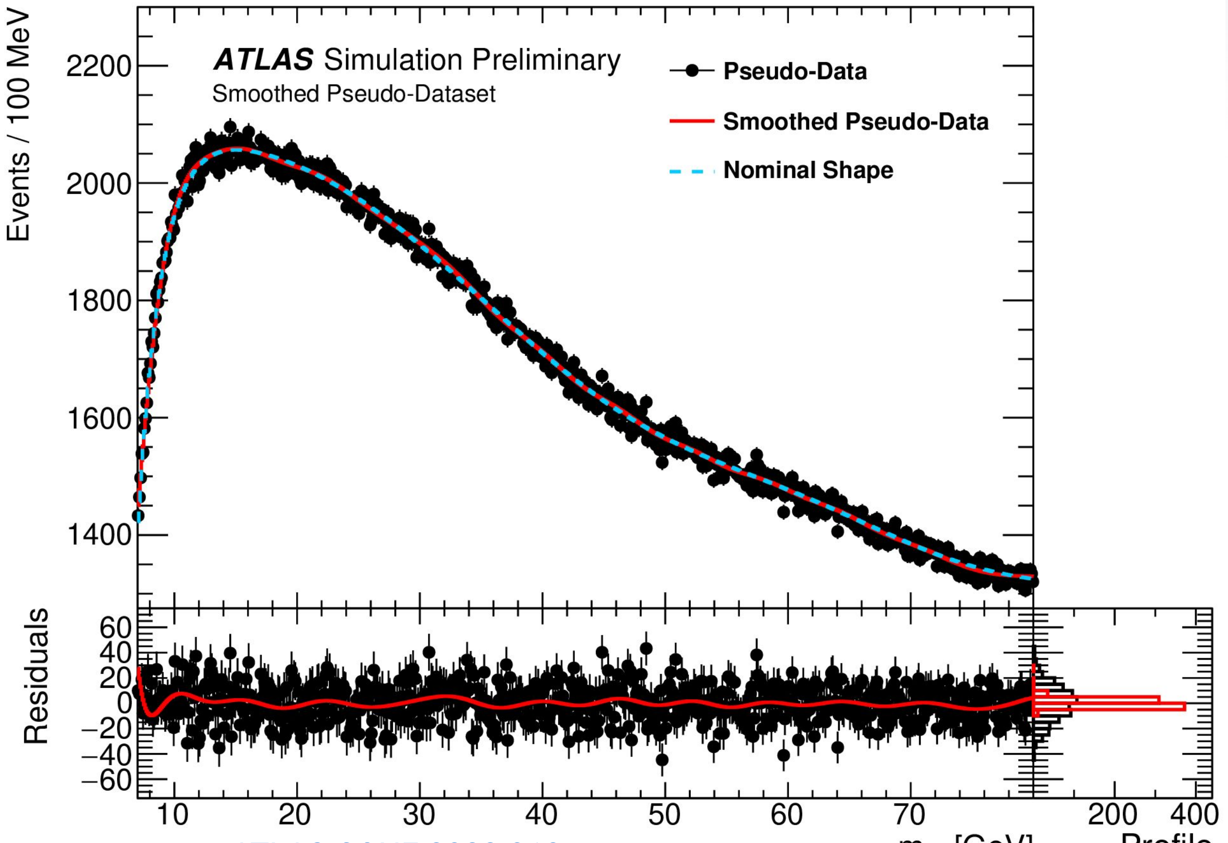
$$= \left[1-(1-f_0)e^{-\frac{m_{\gamma\gamma}-10}{\tau_{flat}}}\right] frac + (1-frac)\left[\underbrace{\left(1-\left(\frac{m_{\gamma\gamma}}{c_1}\right)^{a_0}\right)^{c_0}}_{\text{PowLaw}}\underbrace{\left(1+\frac{e^{\frac{m_{\gamma\gamma}-\delta_{tail}}{\tau_{tail}}}}{1+e^{-\frac{m_{\gamma\gamma}-\delta_{thresh}}{\tau_{thresh}}}}\right)}_{\text{Activation function}}\right]$$

Variations on the template shape are used to evaluate the flexibility of the background modelling :

- different control region definitions
- different $\gamma\gamma$ purity
- varied $p_T^{\gamma\gamma}$ threshold

All variations lead to sizable changes in the spectrum

- all well described with the nominal model



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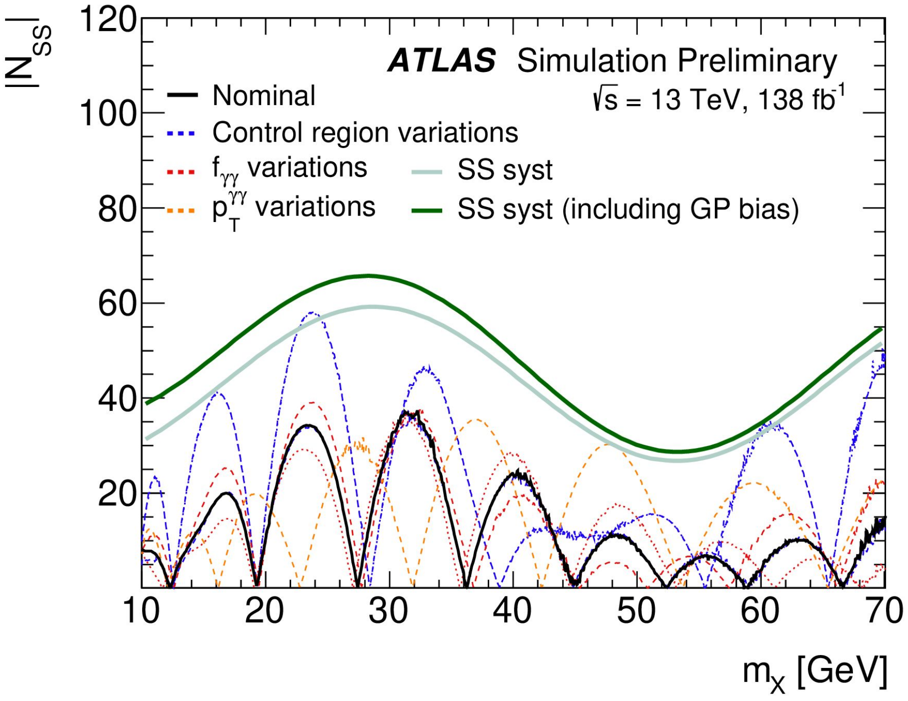
Spurious signal and GPR

Estimation of bias arising from the choice of the background model :

- signal-plus-background fits to background-only templates
- any fitted signal yield is denoted “spurious signal” (SS) and is a systematic uncertainty

Background templates are affected from low statistics :

- the Gaussian Process Regression (GPR) method
  - mitigates statistical fluctuations on the background shape
  - GPR decreases the SS systematics uncertainty
  - the bias from the GPR methodology is also accounted for



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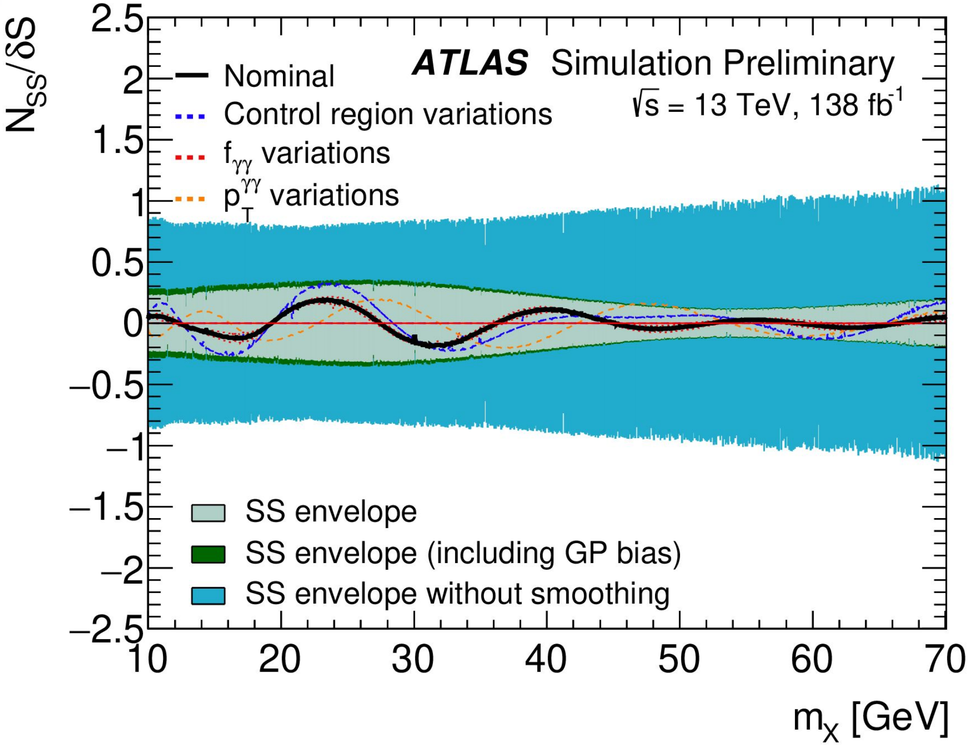

Summary of systematics

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Source	Uncertainty
	On $\sigma_{\text{fid}} \cdot \mathcal{B}(X \to \gamma\gamma)$ [%]
Pile-up modeling	± 3.5 (at 10 GeV) – ± 2 (beyond 15 GeV), mass dependent
Photon energy resolution	± 2.5 – ± 2.7, mass dependent
Scale and PDFs uncertainties	± 2.5 – ± 0.5, mass dependent
Trigger on close-by photons	±2 (at 10 GeV) – < 0.1 (beyond 35 GeV), mass dependent
Photon identification	±2.0
Isolation efficiency	±2.0
Luminosity (2015–2018)	±1.7
Trigger	±1.0
Signal shape modeling	< 1
Photon energy scale	negligible
	Background modeling
Spurious signal (relative to δS)	30-65 events (10-30 %), mass dependent

Most systematic uncertainties are percent-level or smaller

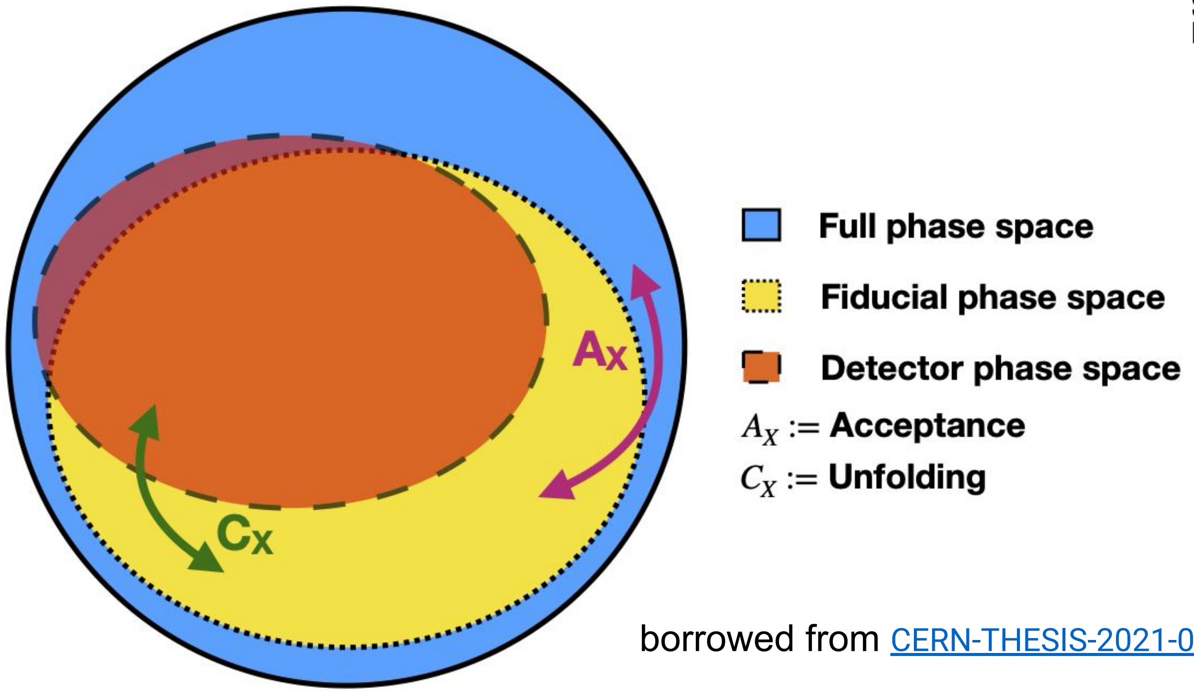
- the dominant systematics arises from the background modelling uncertainties
    - spurious signal (SS) and GPR bias combined

Definition of the fiducial volume

The measurement of the signal production cross-section is performed in a fiducial volume:

- defined at generator level from the signal MC simulation samples
  - $p_T^{\gamma\gamma} > 50$ GeV
  - $E_T > 22$ GeV for each photon
  - particle-level isolation $E_T^{iso} < 0.05 \times E_T$ within a $\Delta R<0.2$ cone

$$\sigma_{\text{fid}} \cdot \mathcal{B}(X \to \gamma\gamma) = \frac{N_S}{C_X \mathcal{L}}, \text{ with } C_X = \frac{N_{\text{MC}}^{\text{det}}}{N_{\text{MC}}^{\text{fid}}}$$



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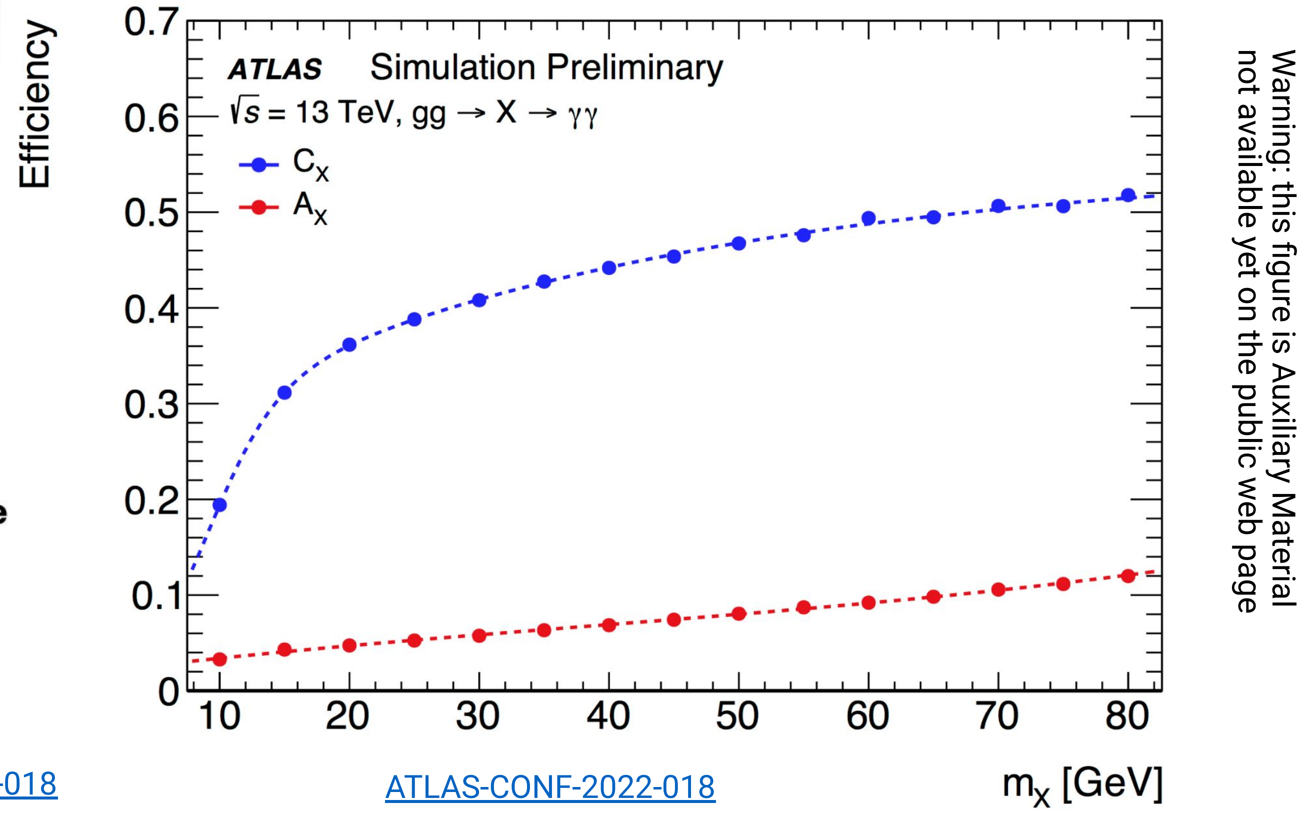

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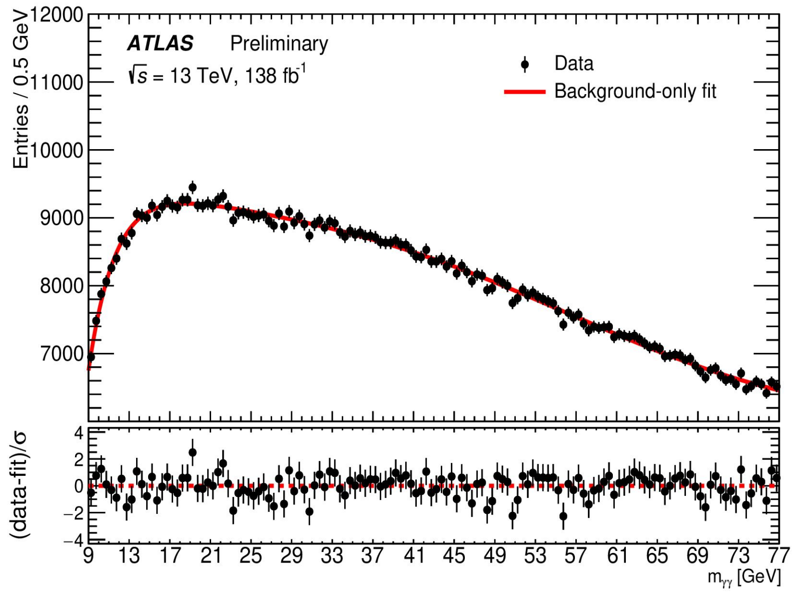
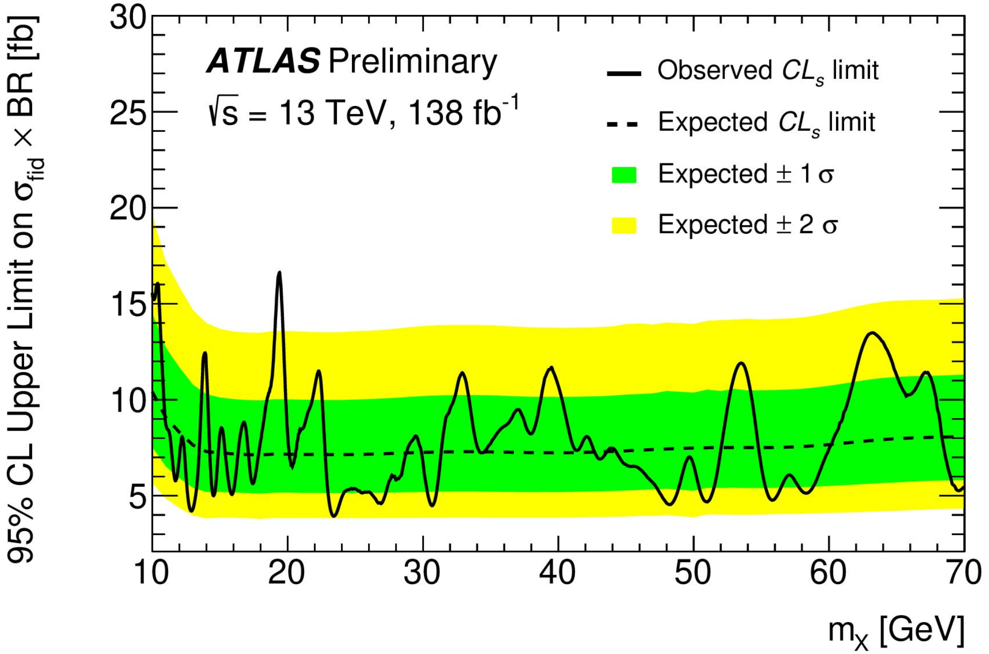
Results

Search performed in the *[10,70] GeV* mass range

- binned likelihood fit in the *[9,77]* range
  - (at least *5σ* lever-arm from edges)
- parameter of interest: $\sigma_{fid}\times BR(X\rightarrow\gamma\gamma)$
- good description of the data with the background model
  - no significant deviation wrt the SM
  - largest deviation at *19.4 GeV*, with *3.1σ* local significance
    - *(1.48±0.02)σ* global significance, evaluated with pseudo-data



Limits set on the $\sigma_{fid}\times BR(X\rightarrow\gamma\gamma)$ of a resonance decaying to two photons



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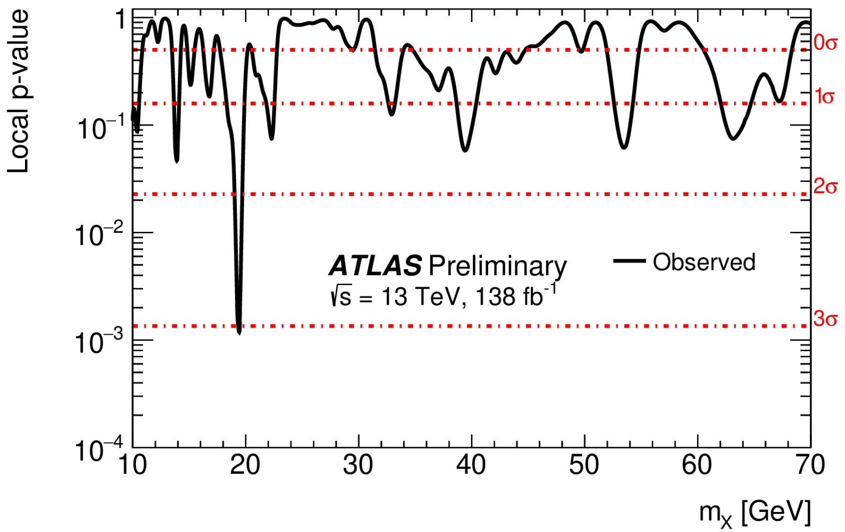
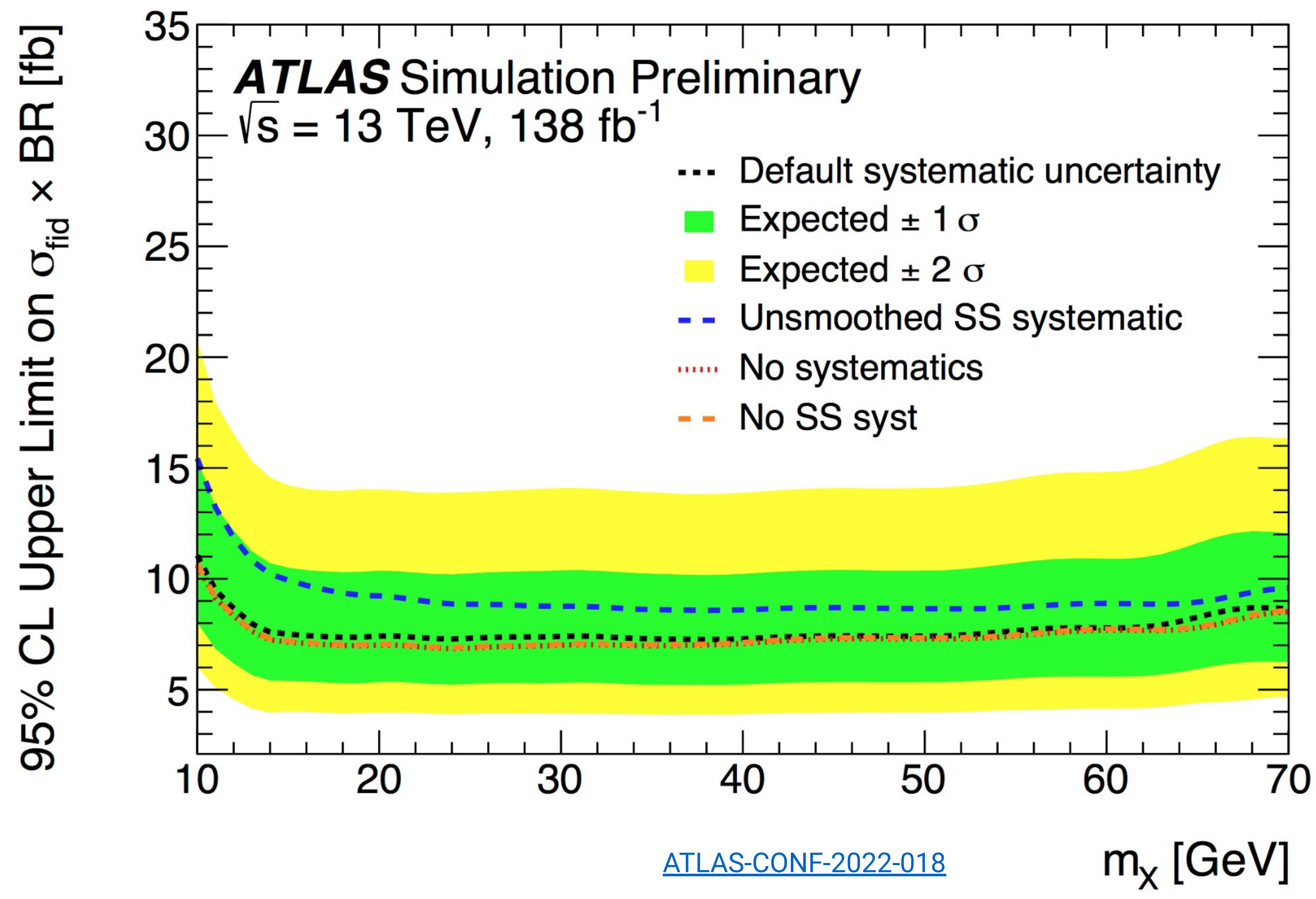


Impact of SS systematics on the limit



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Phenomenological interpretation in terms of an ALP

New Physics scenario being considered:

- all heavy states are beyond the reach of the LHC
  - no deviations from the SM behavior are expected in the TeV range
- a scalar a, singlet of the SM gauge group, naturally lighter than the EW scale exists
  - a is abundantly produced in proton-proton collisions
  - a decays promptly into a pair of SM particles with a narrow width
- a "KSVZ-ALP" model is considered, inspired by the simplest QCD axion model of the scalar a :

$$\mathcal{L}_{\rm int} = \frac{a}{4\pi f_a}\left[\alpha_3 c_3 G^a \tilde{G}^a + \alpha_2 c_2 W^i \tilde{W}^i + \alpha_1 c_1 B\tilde{B}\right]$$

- barring a huge hierarchy among the anomaly coefficients:
  - for $m_a \lesssim m_Z$, the relevant two-body decays of a are to photons and to jets
  - the width into gluons dominates over the one into photons
  - the total width is dominated by its coupling to gluons and is always small compared to its mass

Phenomenological interpretation: ALP landscape

Limits recast into the ALP parameter space

- strongest limits on a hypothetical resonance produced in gluon fusion that decays to two photons

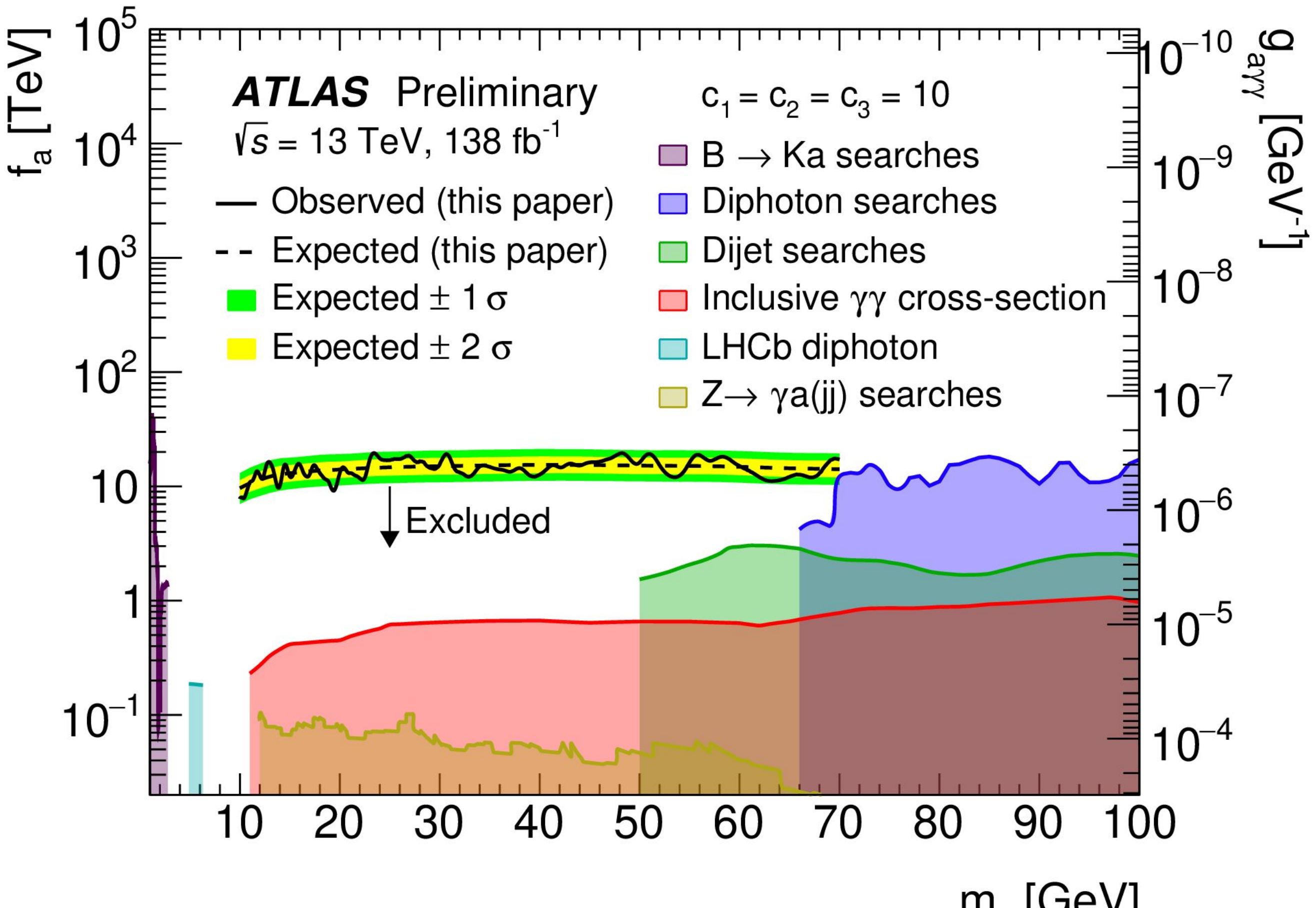
Other searches probing the same mass range:

- light-by-light scattering in heavy ion collisions significantly limited by the production mechanism
- dijet searches disfavoured by mass resolution

Other diphoton searches in proton proton collisions:

- CMS 13 dominates down to *70 GeV* (*35.9 fb^{-1}*)
- ATLAS extends the limit down to *65 GeV* (*80 fb^{-1}*)

A large piece of the $\gamma\gamma$ gap is now covered !



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Summary

ATLAS searched for boosted resonances in the diphoton channel, with masses in the *10* to *70 GeV* range

Analysis strategy:

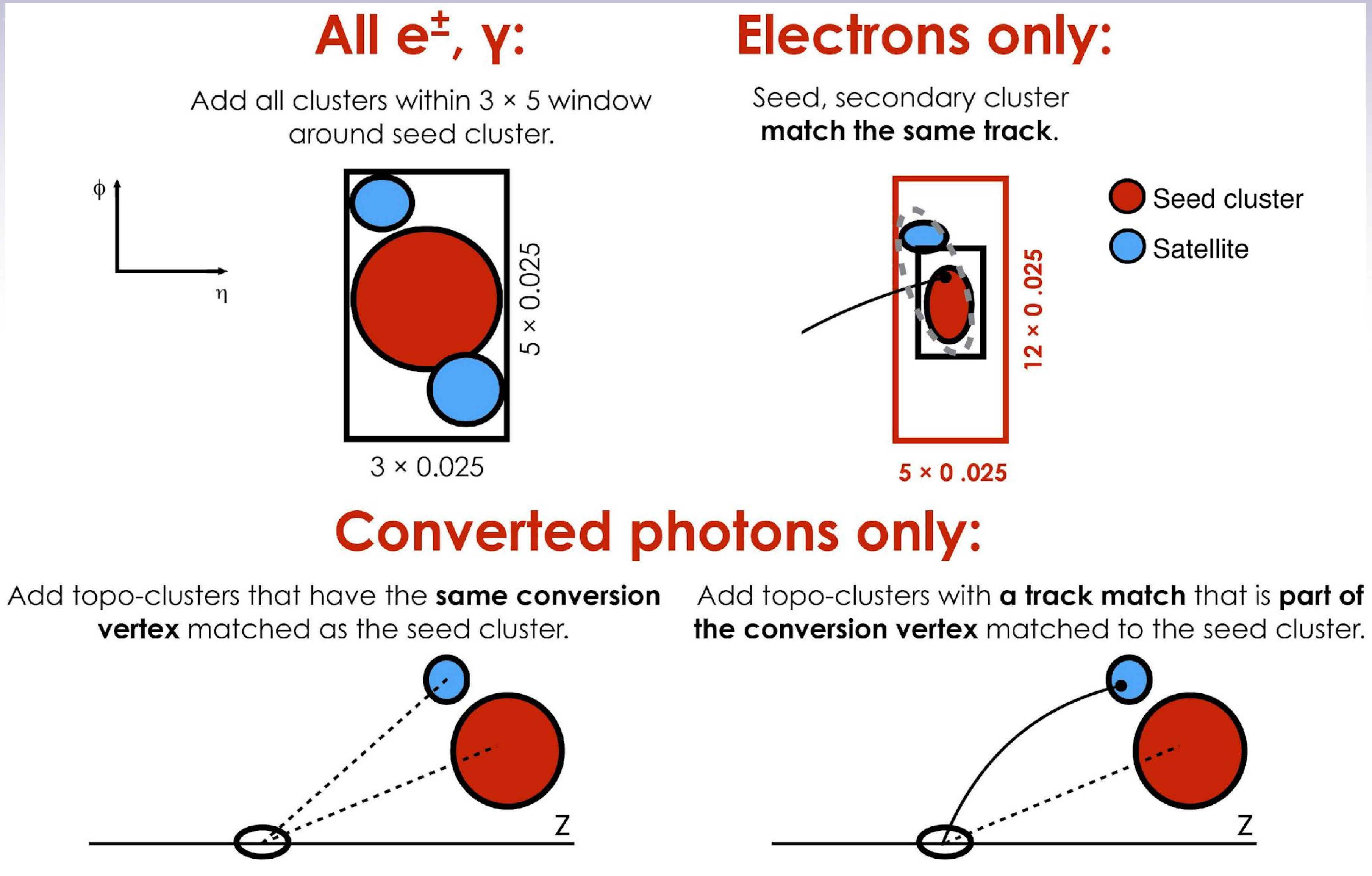
- strongly relies on the excellent performance of the EM calorimeter
- novel selection of boosted diphoton pairs to reach masses below the trigger turn-on
- observed data in agreement with the SM-only (no excess) hypothesis
- largest deviation found at *19.4 GeV*
  - corresponding to a 3.1σ (1.5σ) local (global) significance
- limits on $\sigma_{fid}\times BR(X\rightarrow\gamma\gamma)$ from *4 fb* to *17 fb*
- the total uncertainty is dominated by statistics
  - impact of background modelling mitigated by GPR

This analysis provides the strongest upper limits up to date using pp collisions:

- on the cross-section times branching ratio of a resonance that decays to two photons
- in the mass range below *65 GeV*, and down to *10 GeV*
- and in the ALP parameter space in that same mass range

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2022-018/

Backup : superclusters



Backup: more on the phenomenological interpretation

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